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LIQUEFACTION POTENTIAL OF DAMS AND FOUNDATIONS

Report 7

GEOTECHNICAL EARTHQUAKE ENGINEERING STATE OF THE ART - 1980

by

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This study describes and evaluates important modern developments in geotechnical earthquake engineering. The current state of knowledge allows for the safe design and construction of critical structures subjected to earthquake loadings, although generally the margin of safety that has been incorporated in the design is not known precisely. For evaluation of the seismic stability of existing critical structures, the state of knowledge is sometimes
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inadequate. In the analysis of existing structures, conditions that are clearly safe and that are clearly unsafe can be distinguished. Between these two limits there are some practical cases that fall into a grey area, which will only be narrowed by further research and new full-scale response data.

PREFACE

The investigation reported herein was conducted at the U. S. Army Engineer Waterways Experiment Station (WES) under the sponsorship of the Office, Chief of Engineers (OCE), Department of the Army, as part of CWIS Work Unit 31145 entitled "Liquefaction Potential of Dams and Foundations." The OCE Technical Monitor is Mr. R. R. W. Beene.

The work was performed and this report was prepared by Drs. W. F. Marcuson III, A. G. Franklin, and P. F. Hadala, Earthquake Engineering and Geophysics Division, Geotechnical Laboratory (GL), under the general supervision of Mr. C. L. McAnear, Acting Chief, GL. This report constitutes the basis of a paper prepared and submitted to the VI Southeast Asian Conference on Soil Engineering held in Taipei, Taiwan, in May 1980.

The six previous reports in the Research Report S-76-2 series are as follows:

- Report 1 - Laboratory Standard Penetration Tests on Reid Bedford Model and Ottawa Sands
- Report 2 - Laboratory Standard Penetration Tests on Platte River Sand and Standard Concrete Sand
- Report 3 - Development of an Elastic-Plastic Constitutive Relationship for Saturated Sand
- Report 4 - Determination of an In Situ Density of Sands
- Report 5 - Development of a Constitutive Relation for Simulating the Response of Saturated Cohesionless Soil
- Report 6 - Laboratory Strength of Sands Under Static and Cyclic Loadings

COL Nelson P. Conover, CE, was Commander and Director of the WES during the conduct of this study and the preparation and publication of this report. Mr. Fred R. Brown was Technical Director.

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GEOTECHNICAL EARTHQUAKE ENGINEERING
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PART I: INTRODUCTION

1. The objective of this study is to describe and evaluate important developments in geotechnical earthquake engineering, particularly those of the last fifteen years. Geotechnical earthquake engineering involves the same fundamental issues and problems that affect the whole field of soil dynamics, and of all areas of soil dynamics, earthquake engineering has seen the greatest intensity of research and development effort in the past 15 years (for example, in 1975 approximately $30 million was spent on earthquake-related research, on a world-wide basis, as reported by Lee et al., 1978). Because the authors' experience is primarily in the United States, this discussion primarily reflects the state of the art of practice on the North American continent.

2. From a practical point of view, there are currently two approaches to obtaining engineering solutions to geotechnical earthquake engineering problems: (a) an empirical approach, and (b) a tuned analytical approach. Conceptually, the empirical approach consists of systematically gathering data on past performance and organizing the data in such a way that there are coherent patterns of behavior that can be used to predict future performance. The method is essentially correlative but takes advantage of the degree of understanding of cause and effect relationships that presently exist. The tuned analytical approach is a method of predicting performance based on an analytical model, where the results of past analyses with the model have been compared with field case histories and correction factors have been developed to adjust the predicted values to agree with those that were observed. The use of the latter approach requires the formulation of a workable theoretical model, and thus some understanding of the mechanisms and processes involved. Imperfections of the model and/or

systematic errors in the input data are compensated for by correction factors. In the past 10-15 years, extensive efforts have been devoted to the development of analytical or tuned analytical approaches to solving geotechnical earthquake engineering problems, but there has been a recent shift toward a more equal balance between the empirical and analytical approaches.

PART II: MAJOR ISSUES

3. As major issues in geotechnical earthquake engineering, several areas are of concern because they constrain the ability to solve problems, or are areas of controversy, or are particular foci of effort or attention. They are not all of equal importance, and indeed the concentration of effort and the progress in dealing with these issues have been very uneven.

Liquefaction

4. The fundamentals of the liquefaction mechanism are, at the present time, not adequately understood, in the sense that a model of material behavior that satisfactorily describes liquefaction response and is amenable to numerical analysis cannot now be formulated (Hardin, 1978). In the present state of the art, liquefaction problems are being analyzed with a mixture of theoretical concepts, empirical procedures, and hybrid procedures based on tuned numerical analyses. The issue is a highly controversial one; far from having general agreement on the mechanisms of liquefaction, the profession sometimes cannot even discuss the issue using a set of generally agreed upon definitions of terms (Marcuson, 1978). In this study, the term "liquefaction" is used in an inclusive sense to denote any of various phenomena that involve high pore pressures, rapid loss of shear strength, and excessive deformation in saturated cohesionless soils. Included are phenomena that have been variously referred to in the literature as liquefaction, limited liquefaction, and cyclic mobility (Castro, 1975; Casagrande, 1976; Seed, 1979a).

5. At the present time, there are available an abundance of laboratory data on the liquefaction behavior of saturated clean sands and a limited number of well-documented case histories. Current effort is focused on the seismic performance of medium dense sands, as the performance at the extremes of the density scale is easily predicted. However, the capability to predict the response of silty sands or gravelly

sands is deficient. This deficiency is caused partially by a lack of understanding of the fundamentals of liquefaction and partially by limitations in the ability to perform adequate laboratory tests.

Limitations on Behavioral Models

6. Stress-strain-time relationships express mathematically whatever is known or hypothesized about the behavior of a material and are used in mathematical models to analyze the behavior of physical systems. The stress-strain-time relationships that are presently used in dynamic analyses are physically imperfect, but these imperfections are not serious constraints on the engineer's ability to use analysis to obtain useful insights into engineering problems. The various mathematical models available in the present state of the art do not describe all aspects of soil behavior equally well (Hardin, 1978). Therefore, obtaining a workable engineering solution to a problem depends on the selection of a mathematical model that best describes the particular aspect of behavior that is of interest, and the selection of laboratory tests that are best suited to measuring the parameters of that model. For instance, at the present time different models must be used in the solution of wave propagation problems and dynamic strength problems.

7. Assuming that an appropriate model is used, a greater degree of uncertainty is produced in the results by imperfect knowledge of the input parameters than by defects in the models themselves; thus, the importance of model defects is relatively minor. The input parameter values are obtained through field exploration and laboratory testing programs. To put the matter into perspective, consider that most of the computer codes and mathematical models that represent the current state of the art were developed in the 1970's (Lysmer, 1978); state-of-the-art laboratory tests were developed in the 1960's (Woods, 1978); and state-of-the-art methods of obtaining undisturbed samples were developed in the 1940's ("State of the Art on Current Practice of Soil Sampling," 1979).

Analytical Procedures

8. The development of analytical procedures is relatively far advanced, so that the degree of sophistication that has been achieved is ahead of the present ability to provide input data good enough to make full use of the analyses. The late 1960's and the 1970's have seen the development of sophisticated one-dimensional, two-dimensional, and three-dimensional methods of analysis of dynamic stress wave propagation, using both linear and nonlinear stress-strain-time relationships as well as the equivalent linear approach, which involves some features of both. These methods all involve the solution of the wave equation, and their common objective is to obtain time variation of shear stress within earth materials. The solution is accomplished by closed form, characteristic, finite element, or finite difference methods. The latter offers an advantage of greater flexibility in the use of sophisticated material stress-strain-time relationships (Lysmer, 1978).

9. Probably the most keenly felt limitation in current methods of analysis is that none of them are capable of reliably predicting deformations, using either simple or complex mathematical models. The shortcomings lie partly in the stress-strain-time relationships, partly in the problems of adequately determining moduli for tests on so-called undisturbed samples, and partly in the analytical procedures themselves. Computation of dynamic displacements and deformations involves integration of accelerations and progressive amplification of relatively small errors in those values. On the other hand, stresses can be computed with fair reliability so long as relative stiffnesses and masses are known, because these calculations rely primarily on a balance of forces, including inertial forces.

Determination of Soil Properties

Field methods

10. In practice, field measurement of dynamic properties of soils usually involves measurement of compression (P) wave and shear (S) wave

velocities, from which dynamic modulus values (applicable to a particular range of stress and strain levels) can be computed, using seismic exploration techniques (Ballard and McLean, 1975). The past decade has seen considerable development in geophysical instrumentation and field techniques, including seismic sources and detectors for use in boreholes, improvements in shear wave sources, improvements in interpretation methods, and the use of "signal enhancement" that involves the use of a series of impulses and the algebraic summing of the successive signals received at the detector in order to improve the signal to noise ratio (Woods, 1978). These methods involve the response of soils at low strain levels (about 10^{-4} percent) so that the modulus values obtained approximate the initial tangent moduli. Some work has been done in recent years on large-strain seismic velocity tests (Shannon & Wilson, and Agbabian & Associates, 1979), but this has not developed yet to the point where such tests are in routine use. Figure 1 summarizes the shear strain amplitude capabilities of field techniques. The determination of variations in moduli with strain level now routinely relies on supplementary tests performed in the laboratory. An additional limitation is that there is at the present time no method for the measurement of material damping values in the field, and this parameter is particularly critical in the analysis of soil-structure interaction.

11. A sometimes worrisome problem is that seismic wave velocities measured by different investigators show greater variations than would be

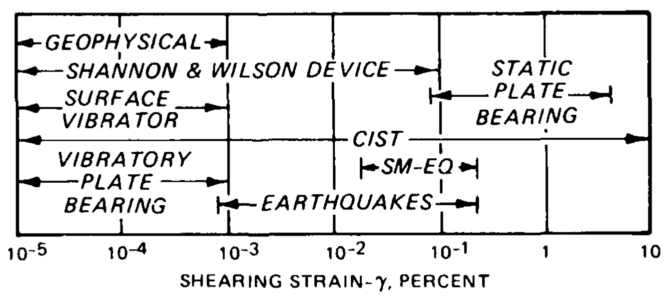

Figure 1. Shearing strain cmplitude capabilities of field techniques (courtesy of R. D. Woods, "Measurement of Dynamic Soil Properties," Conference of Earthquake Engineering and Soils Dynamics, American Society of Civil Engineers, Vol 1, 1978, pp 91-180)

expected in an apparently simple physical measurement. These inconsistencies are not easily explained, but most of the common errors involve such things as unaccounted for detonator delays or borehole deviations, and too much distance between source and receiver resulting in a travel path less direct (i.e., refracted through adjacent higher velocity zones) than the path assumed, so that the reported velocity values are too high. Generally, refinements in wave velocity measurement techniques result in lower velocities being measured. Table 1 summarizes the current techniques for measuring in situ dynamic soil properties.

12. With regard to evaluation of liquefaction potential, field testing methods are generally not applicable to the direct determination of soil parameters, other than density, related to liquefaction behavior. The Standard Penetration Test (SPT) is used in empirical evaluation of liquefaction potential, and other field tests such as the cone penetrometer test have the potential for being used in the same way. The difficulties encountered in evaluating liquefaction potential through laboratory tests led to the consideration of in situ testing methods for a remedy. However, a general limitation in this approach is the inability to control or even to know the in situ state of stress, the drainage condition, and the volume or mass of material involved. Consequently, most in situ tests are usable for this purpose only as index tests and rely on correlation with laboratory response and/or field observations of earthquake effects.

Laboratory methods

13. In the current state of the art, production testing uses the stress-controlled cyclic triaxial test to evaluate liquefaction potential and the strain-controlled cyclic triaxial test or the resonant column test to measure modulus and damping. It is generally recognized that the stress-controlled cyclic triaxial test has serious shortcomings: (a) it does not correctly represent the state of stress that is believed or assumed to exist in the field, and (b) it involves reversals of the principal stresses that are not believed to occur in the field. Other possibilities have been and are being explored, such as large-scale shake table

tests, hollow cylinder torsional tests, and simple shear box tests. All of these alternatives have problems that have not yet been overcome, such as difficulties in preparing specimens, difficulties in applying shearing forces at the specimen boundaries, and nonuniformity of strain distribution.

14. One of the most troublesome problems in laboratory testing of soils is that of sample disturbance, particularly in sands. Relatively recent research has shown that structure is much more important in the behavior of sands than had previously been thought, and that sand samples compacted to a given density in the laboratory can have different structures and different cyclic strength responses, depending on the method of sample preparation (Ladd, 1974; Mulilis, Chan, and Seed, 1975; Marcuson and Townsend, 1976; Mori, Seed, and Chan, 1978). These circumstances make the use of undisturbed samples imperative, but the present field sampling technology represents the state of the art of the 1940's (Hvorslev, 1949; American Society of Civil Engineers, 1978; Marcuson and Franklin, 1979; Horn, 1979).

15. On a more fundamental level, the very design of a laboratory test reflects current concepts and practice in the formulation of stress-strain-time relationships, since the tests are designed to measure the parameters contained in these relationships. The ideal laboratory soil tests should (a) impose the stresses anticipated in the field on the test specimen, (b) have uniform and known stresses throughout the specimen, and (c) be conducted on test specimens truly representative of the material in situ. The laboratory tests that come closest to imposing the expected field stress conditions, e.g., the simple shear box, the hollow cylinder torsional test, and the shake table test, are not well suited to the use of undisturbed samples and do not stress the specimen uniformly throughout. The cyclic triaxial test is now used in practice despite its nonuniformity of stresses and the occurrence of stress reversals that are considered not representative of actual field conditions. The continued use of the cyclic triaxial test is justified by an overriding need to get on with the job and its convenience for use with undisturbed samples.

16. Table 2 summarizes the current laboratory techniques for measurement of dynamic soil properties and the properties obtained from each test. Figure 2 shows the shear strain amplitude capabilities of the various tests.

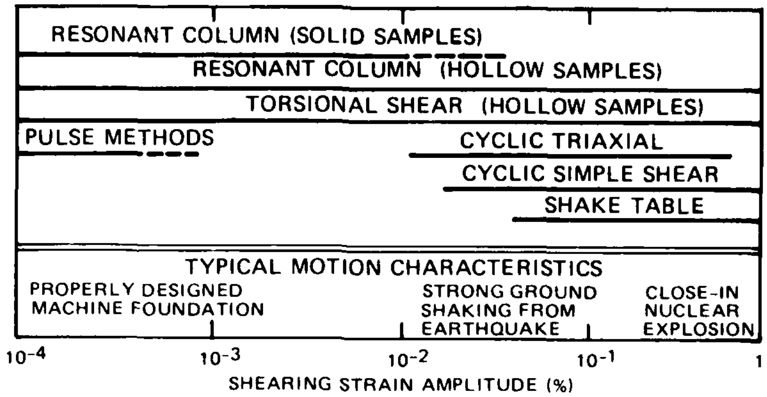

Figure 2. Shearing strain amplitude capabilities of laboratory apparatus (courtesy of R. D. Woods, "Measurement of Dynamic Soil Properties," Conference on Earthquake Engineering and Soils Dynamics, American Society of Civil Engineers, Vol 1, 1978, pp 91-180)

Prediction/Characterization of Load Functions

17. In seismic response problems, the load function is the earthquake ground motion, and its prediction properly belongs to the sphere of seismology. However, the ground motions are usually the most critical part of the input to a dynamic analysis, and it is necessary to specify the input motion in such a way as to have a well-posed problem for the dynamic analysis (Idriss, 1978). In order to ensure that the specified loading function (the design earthquake) is realistic in view of the site geology and the regional seismicity, and in addition that it is specified in a way that is appropriate for the structure involved, the selection of the design earthquake should be a team effort, involving interaction of seismologists, geologists, and geotechnical and/or structural engineers. The choice of a design earthquake conventionally involves the choice of such parameters of the ground motion as the

maximum acceleration, maximum velocity, and the duration of strong motion (usually motion equal to or greater than 0.05 g). However, it is generally recognized that the specification of these parameters is not sufficient to define the characteristics of the loading function, so one or more acceleration versus time records from some sites of similar geology, from earthquakes of about the same magnitude and epicentral distance, and scaled to give the same peak motion parameters are chosen as loading functions. Some of the more important issues involved in the specification of the loading function are discussed in the following paragraphs.

Data base

18. The United States, and the world, has experienced in the last decade a tremendous expansion in systems of strong motion instrumentation and will see in the next decade or two concomitant expansion in the available inventory of strong motion records. At the present time, however, there are some noticeable gaps in our strong motion data base. A large portion of the United States strong motion data base consists of records obtained during the San Fernando Earthquake of 1971. Our inventory is totally lacking in close-in strong motion data from earthquakes of magnitudes 7.0 and greater. In addition, most of the available data represent surface motions, while it would be desirable to have documentation of motions occurring in the subsurface. An additional, and acutely felt, deficiency is in strong motion records that can be closely correlated with records of performance of dams and other structures during past earthquakes. Such case histories would be highly desirable for the purpose of validating our analytical methods.

Location of input motion

19. A serious question in dynamic analysis is that of where to apply the input loading function. Commonly, the input motion is applied at the surface of the bedrock, but it is clearly inappropriate to apply in this manner a record obtained at the ground surface. The soil or overburden layer acts as a filter in the propagation of ground motions upward from the bedrock. A weak layer can filter out important parts of the ground motion, as we have seen in strong motion records from Niigata,

Japan, where very weak motions were measured at the surface in areas where liquefaction occurred (Seed and Idriss, 1967). Conventional practice is to obtain relations between ground motion at different levels by means of a one-dimensional wave propagation analysis. However, a one-dimensional analysis ignores lateral inhomogeneities in the soil as well as the decay of surface waves with depth.

Frequency content

20. The design input motions will not adequately test a structure if they are deficient in frequencies in the neighborhood of the fundamental frequency of the structure, unless that fundamental frequency is either a very high or a very low one that does not normally occur in earthquakes. Spectral representations of the ground motions, such as response spectra, Fourier spectra, and power spectral densities, while not generally used directly in geotechnical analyses, are useful descriptors of the character of the ground motion that should be considered in selecting the design earthquake (Christian, 1980). Spectral representations may also be used as the starting point in the generation of synthetic earthquakes (Jennings, Housner, and Tsai, 1968; Liu, 1970), which may serve as an alternative to a natural earthquake record. Such records are derived from smooth enveloping spectra, while the spectra of natural earthquakes are irregular and lie under the envelope at many frequencies. Thus, the synthetic record represents too severe a motion.

PART III: SIGNIFICANT MODERN DEVELOPMENTS OR EVENTS

The Good Friday Earthquake in Alaska (27 March 1964)

21. The Good Friday earthquake produced spectacular damage and occurrences of ground failures, but little useful ground motion data (Seed and Wilson, 1967). However, it produced a heightening of awareness of earthquake problems in the United States and instigated appropriations and research to deal with earthquake problems.

The Niigata, Japan, Earthquake (16 June 1964)

22. The Niigata earthquake is noteworthy especially for the spectacular effects produced by liquefaction-type ground failure. Modern structures in Niigata were seismically designed and had adequate strength to resist shaking. However, because they were not designed to float, a number of buildings overturned when the ground liquefied under them (Kishida, 1966). Other evidences of liquefaction, such as sand boils, were widespread. After the earthquake, the airport lay under a foot of water. Postearthquake investigations in Niigata revealed useful correlations between SPT blowcounts and occurrences or nonoccurrences of liquefaction (Koizumi, 1966; Ohsaki, 1966 and 1969), gave impetus to earthquake engineering research internationally, and were the basis for liquefaction research during the next decade.

The San Fernando Earthquake (9 February 1971)

23. Damage and loss of life during this earthquake were a source of widespread concern. The slide in the Lower San Fernando Dam during this earthquake narrowly missed becoming the largest single disaster in United States history, since an estimated 80,000 people living downstream were threatened. The potential overtopping failure of the dam did not occur only because the water level was below maximum pool (Seed et al., 1975). This earthquake doubled our catalog of strong motion data, offering

opportunities for the study of effects of site conditions on ground motions and empirical correlations of ground motions with performance of structures. It is notable that there were five hydraulic-fill dams that were subjected to accelerations of approximately 0.2 g without incurring serious damage (Seed, Makdisi, and De Alba, 1978). On the other side of the coin, the fact that so large a part of the existing data base represents a single earthquake introduces an unknown bias into the statistical characteristics of ground motions and empirical correlations. The strong motion record obtained at an abutment of Pacoima Dam (a concrete structure) during this earthquake represented the first time that accelerations in excess of 1.0 g have been instrumentally recorded.

Advances in Numerical Methods

24. The development of computer codes for one-dimensional and two-dimensional dynamic analyses have had a far-reaching influence in earthquake engineering. Studies made with the use of these tools have provided a better understanding of the effects of site conditions on ground motions and the relative importance of various geotechnical parameters in influencing ground motions and soil-structure interaction (Lysmer, 1978). The codes have also made possible the use of more realistic and sophisticated models of material and structural behavior.

Development of Cyclic Laboratory Tests

25. The cyclic triaxial, resonant column, simple shear, and shake table tests have had a major influence on the practice of geotechnical earthquake engineering. These tests have provided quantitative indices of the influence of void ratio and stress level on pore pressure development and liquefaction potential in cohesionless soils and of the influence of strain levels on stiffness and damping (Woods, 1978). Cyclic testing methods are an indispensable part of a rational approach to the evaluation of liquefaction problems.

Development of a Coherent Approach to Liquefaction Problems

26. The relationship between the liquefaction potential of a cohesionless soil and its density state was fully recognized by Casagrande (1936), who described the concept of a "critical density," which is a function of the confining pressure. The critical density concept has been extended and refined by Castro (1975) and Casagrande (1976) in terms of a critical state line on a pressure-density plot, which is established through monotonic, stress-controlled, consolidated-undrained triaxial shear tests with pore pressure measurements. This approach is particularly valuable for evaluating the potential of cohesionless soil deposits to spontaneous liquefaction.

27. During the 1960's and 1970's, the so-called "Seed approach" to seismic analysis of liquefaction problems was evolved, primarily through work at the University of California at Berkeley. This approach has been used for the dynamic analysis of a number of major dams and has been applied in a back calculation mode to the slides in the Upper and Lower San Fernando Dams and to the failure in Sheffield Dam (Seed, Lee, and Idriss, 1969; Seed et al., 1973 and 1975).

Analysis of Postearthquake Pore Pressure Redistribution

28. Analysis of seismoscope records from the Lower San Fernando Dam indicated that the slide actually occurred a short time after the earthquake shaking had ceased; redistribution of earthquake-induced pore pressures was inferred as the reason for the delayed slide. Computer codes for the analysis of postearthquake pore pressure redistribution have since been developed (Seed, 1979b). Generally, the permeability variation within the embankment and foundation materials are not known accurately enough to permit a high level of quantitative accuracy. However, recognition of the significance of postearthquake pore pressure redistribution and possible resulting instability at a later time is important as an identification of a possible failure mechanism that had

not been previously recognized. One effect this may have on the practice of seismic analysis is to place more importance on the analysis of the effects of strong aftershocks, which would find the dam in a temporarily weakened condition.

Permanent Displacement Analysis

29. A method of analysis that treats a slide in an embankment as a rigid block on an inclined plane, subjected to earthquake accelerations, was proposed by Newmark (1965), and a coherent analytical procedure has evolved on the basis of this concept (Goodman and Seed, 1966; Ambraseys and Sarma, 1967; Sarma, 1975 and 1979; Franklin and Chang, 1977; Makdisi and Seed, 1977). This procedure offers a rational basis for the anlaysis and design of earth and rock-fill dams that do not involve materials which might be susceptible to liquefaction. The somewhat limited experience with this procedure up to the present time indicates that in earth dams of cohesive materials and in rock-fill dams with highly permeable shells which are not susceptible to liquefaction, if there is a satisfactory static factor of safety, direct damage, even from major earthquakes, should be limited to relatively minor cracking or sliding.

Development of In Situ Testing and Sampling

30. At the present time, there is a discernible trend toward greater emphasis on in situ testing and improvement of sampling methods. Studies have been made on the reliability and causes of variability in the SPT test (American Society of Civil Engineers, 1975), as well as on the efforts to standardize the test. One notable development still in the research stage is the piezometer probe that measures induced pore pressures while being pushed into the soil. The probe may provide useful information on the liquefaction susceptibility of cohesionless soils by responding to the pore pressures induced by the collapsing or dilantant behavior of the soil (Torstensson, 1975; Wissa, Martin, and Garlanger, 1975; Schmertmann, 1978). Another tool under development is

the dynamic pressuremeter (Mori, 1979). This equipment appears capable of measuring the in situ shear modulus over a range of strain levels and may offer the potential for obtaining in situ values of damping over similar ranges of strains. A great deal of effort is going into refinement of geophysical testing methods, particularly in measurements of S-wave velocity. In the field of sampling of soils, an increasing need exists for high-quality undisturbed samples of cohesionless soils for laboratory tests of liquefaction susceptibility. Until the 1970's, the significance of structure in influencing the mechanical behavior of sands was not recognized; it was merely assumed that a sample of sand recompacted to in situ density in the laboratory was adequately representative of its in situ behavior. Recent research has shown that this assumption is unjustified and that, moreover, the effects of disturbance caused by even the most careful conventional sampling practice are serious (Mulilis et al., 1977; Mori, Seed, and Chan, 1978; Marcuson and Franklin, 1979). A breakthrough of considerable potential importance is the experimental proof that sands may be frozen without discernible effects on their structure, provided that free drainage is permitted away from the freezing front and the effective stress state is maintained during freezing (Yoshimi, Hatanaka, and Oh-Oka, 1977 and 1978; Walberg, 1978; Singh, Seed, and Chan, 1979). Freezing was used to aid in sampling by the Corps of Engineers at Fort Peck Dam in 1939 (Middlebrooks, 1942) but has been little used since. Yoshimi, Hatanaka, and Oh-Oka (1977 and 1978) report the use of radial freezing to obtain undisturbed field samples of saturated sand, but the technique they used appears to be limited to shallow ($\sim$10 m) exploration. Development of a reasonably economical field technique that can be used to moderate depths ($\sim$50 m) remains to be accomplished.

Strong Motion Instrumentation

31. The past decade and a half has seen a vast expansion in the number of strong motion instrumentation arrays through much of the world. The first major payoff was seen in the United States at the time of the

1971 San Fernando earthquake when more than 100 stations produced useful strong motion records. It is to be expected that future large earthquakes, particularly in California, will produce so many new records that they will have to be used quite selectively (Iwan, 1978). The emphasis will likely be on filling gaps in the data base, particularly the lack of records of nearby earthquakes of magnitude 7.0 and above, and on securing records that will document the response of particular structures to earthquakes. An important recent example of response data is the El Infiernillo Dam in Mexico. It was shaken by a strong earthquake (magnitude = 7.7) in 1979 but experienced only minor damage. Strong motion records were obtained at three levels in the embankment. Study of records of this type, together with observations of performance, will be invaluable in validating analytical methods.

PART IV: CURRENT TRENDS

32. From an examination of the discussions above, several trends in geotechnical earthquake engineering emerge. As mentioned earlier, there is a trend toward a better balance between analytical and empirical approaches to soil dynamics problems, and particularly in efforts to assemble and evaluate more empirical data on past performance of structures. Advances in the various aspects of geotechnical earthquake engineering have been uneven. In particular, the development of analytical approaches and computer codes to implement them have reached a level of sophistication such that the input data, rather than the analytical models, now govern the accuracy of the analysis. Additionally, the analytical methods need empirical validation, but at the present time a sufficient number of well-documented case histories are lacking. Closer studies are now being made of past failures or past performance of structures that have undergone earthquakes (Seed, Makdisi, and De Alba, 1978).

33. Laboratory research to attempt to explain the cyclic mobility of medium dense sands via exploration of differences in response during extension and compression stress paths is under way. This limited research to date indicates that the reversal of principal stress directions tends to erase the strength derived from past stress history (Tatsuoka and Ishihara, 1974).

34. An effective stress approach is being used for one-dimensional analysis of earthquake-induced pore pressure development (Finn, Lee, and Martin, 1977 and 1978). Input data are obtained from constant volume, drained, cyclic simple shear tests. If the method is validated against field behavior, it can circumvent the host of problems associated with the cyclic triaxial test and can offer the potential for computing seismically induced settlements.

35. The implementation of strong motion instrumentation continues. Strong motion instruments have themselves been improved in recent years, and a better understanding now exists of where and how to place them in

order to obtain the most meaningful strong-motion data. While there are only a few major earthquake events worldwide each year, the capability to learn as much as possible from most of them has improved. It is to be expected that the inventory of strong-motion records will increase rapidly in the next decade.

36. An increased concentration of effort in the area of field exploration, particularly the development of improved sampling methods and methods of in situ testing of liquefaction potential and other dynamic properties of soils, has been noted. Such efforts at the present time include the refinement of the SPT, the study and more widespread use of the cone penetrometer test, and the use of piezometer probes, dynamic pressuremeters, and geophysical methods, including nuclear and electrical methods directed at measuring in situ density. The measurement of in situ properties by means of seismic test methods has already seen a great deal of development and has long since attained the status of routine test methods.

37. There are two areas where little significant work is in progress in geotechnical earthquake engineering. One is the development of laboratory tests that meet the requirements of an ideal test as stated earlier in paragraph 15. The other is in the development of better undisturbed sampling methods. With the exception of in situ one-dimensional freezing, it is essentially the technology of the 1940's that is being used.

PART V: CONCLUSIONS

38. In geotechnical earthquake engineering, the current state of knowledge allows for the safe design and construction of critical structures that may be subjected to earthquake loadings; however, the margin of safety that has been incorporated in current procedures cannot be evaluated precisely. For the evaluation of the seismic stability of existing critical structures, such as some dams and nuclear power plants, the state of knowledge is sometimes inadequate. In the analysis of existing structures, conditions that are clearly safe and conditions that are clearly unsafe can be defined. Between these two limits lie some practical cases that fall into a grey area, which will only be narrowed by continued intensive research and new full-scale response data.

39. Current seismic design methodology does not rigorously account for all cause and effect relationships. However, correction factors and compensating errors allow past experience to be "predicted," and in this way calculational techniques have been tuned or calibrated. More case histories are needed to further develop and refine current approaches.

40. It is recognized that existing numerical dynamic stress analysis capabilities are much more advanced than the ability to obtain representative undisturbed soil samples and to test them under the correct stress-strain conditions in the laboratory. Ongoing research in the area of in situ testing offers hope of being able to obtain in the future more reliable soil properties and parameters, thus circumventing our sampling and laboratory shortcomings.

41. Also, it is believed that the strong motion instrumentation arrays that are in place and being expanded will provide the data that will fill the present gap existing in the data base. This gap includes close-in records from earthquakes of magnitude 7.0 and greater.

42. In the final analysis, it should be realized that laboratory tests and analytical calculations are done not for the sake of numerical results obtained, but for the purpose of understanding and extending a limited field data base so that sound engineering judgments can be made regarding the safety of structures.

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Table 1

Field Techniques for Measuring Dynamic Soil Properties*

Field Technique	P-Wave Velocity	S-Wave Velocity	Other Measurements	Advantages	Disadvantages
Seismic refraction	X	X	Depths and slopes of layers	Reversible polarity with SH-wave** Work from surface Samples large zone Preliminary studies	Miss low-velocity zones Low strain amplitudes Properties measured are for thin zones near boundaries
Cross-hole Seismic	X	X		Reversible poliarity	Needs two or more holes
(In situ impulse test)	X	X	Velocity as function of strain amplitude	Works in limited space Finds low velocity	Holes must be surveyed for verticality Needs short-time interval resolution
Down-hole (Up-hole) Seismic	X	X		One hole Reversible polarity Finds low velocity Works in limited space	Measure average velocities Ambient noise near surface Low strain amplitude
Surface vibration		X	Attenuation of Rayleigh wave	Work from surface	Uncertain about effective depth Needs large vibrator
SPT			Empirical correlation with liquefaction	Widely available Widely used in past	Needs "standardization"
Resonant footing			Modulus of near surface of soils	Work from surface	Limited depth of influence
Water cannon			Dynamic stiffness of support	Work from surface	Apparatus and analysis very elaborate
CIST	X	X	Constitutive Eq.	Wide amplitude range	Very elaborate

* Courtesy of R. D. Woods, "Measurement of Dynamic Soil Properties," Conference on Earthquake Engineering and Soils Dynamics, American Society of Civil Engineers, Vol 1, 1978, pp 91-180.

** Horizontally polarized shear wave.

Table 2

Laboratory Techniques for Measuring Dynamic Soil Properties*

Tests	Shear Modulus	Young's Modulus	Material Damping	Cyclic Stress Behavior	Attenuation
Resonant column	X	X	X		
(With adaptation)					X
Ultrasonic pulse	X	X			X
Cyclic triaxial		X	X	X	
Cyclic simple shear	X		X	X	
Cyclic torsional shear	X		X	X	
Shake table	X			X	

* Courtesy of R. D. Woods, "Measurement of Dynamic Soil Properties," Conference on Earthquake Engineering and Soils Dynamics, American Society of Civil Engineers, Vol 1, 1978, pp 91-180.

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